Scale-up of Planar Solid Oxide Stack Technology for MW-class Power Systems

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This study aimed to identify scale-up/integration issues in the use of modular anode-supported planar SOFC stacks for MW-class systems.

- Planar anode-supported SOFC design offers high power densities (lower cost) but implications are unclear for hybrid system operation.
- Our objective was to evaluate the attractiveness of integrating SECA-style planar stacks into MW-scale systems, including hybridization.
  - Define boundary conditions for MW-scale planar SOFC stack in the context of a MW-scale hybrid system
  - Analyze cell performance and stresses to evaluate effects of operating conditions and size for radial-flow planar cells
  - Perform high-level analysis of system-level performance and cost of planar SOFC-based hybrid systems at design point.

In particular, this study aimed to investigate the critical operational and performance issues to design and scale-up stacks for the MW-scale system.

This presentation will discuss the implications of stack design and operating conditions for SOFC stack and system performance.

- We developed an anode-supported SOFC cell/stack model to assess the implications for scaling up designs for MW-scale systems
- In particular, the model was used to answer the following questions:
  - How would internal reforming in the stack effect the power density, parasitic losses, and thermal stresses?
  - How would the operating pressure affect the stack performance?
  - How would the inlet air and fuel temperature affect the stack performance?
  - What are the implications of area scale-up for stack stresses, fuel utilization, pressure drops, etc.?

Analysis requires definition of a stack architecture and relevant system configuration to define the system boundary conditions.

For this investigation, we used our SOFC model, which helps estimate the performance parameters, to guide the stack / system design and scale-up.

Operating Conditions

- Inlet Temperature
- Operating Pressure
- Fuel Composition
- Fuel and Air Flow Rates
- Cell Voltage

Fuel Cell Design

- Cell Architecture
- Cell Size
- Materials Properties
- Contact Resistance

SOFC Model

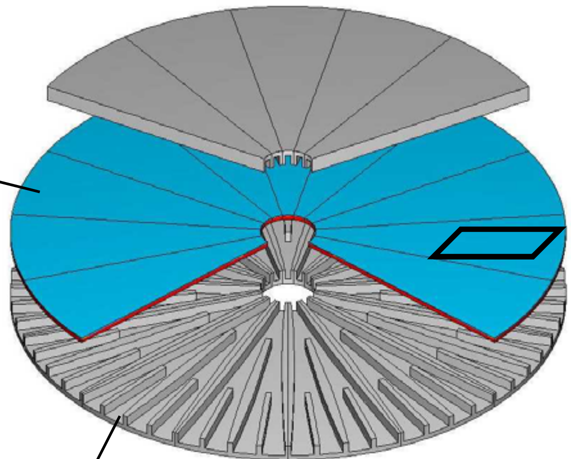
- Electrochemistry
- Reactants Chemistry
- Thermal
- Mechanical Stresses

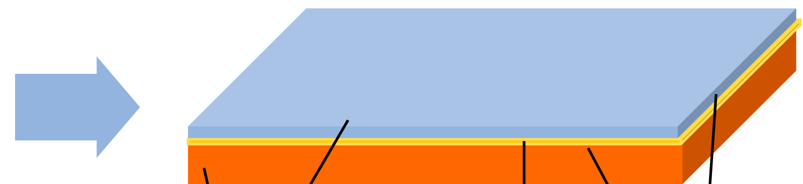
Performance parameters that influence stack and system design

- Mechanical Stress Distribution
- Power Density Distribution
- Temperature Distribution
- Fuel Utilization
- Exhaust Temperature

The SOFC model accounts for all the relevant electrical, chemical, thermal, and mechanical phenomena, which influence cell performance.

Electrode Electrolyte Interface (EEA)
- Electrochemical & chemical reactions
- Ion conduction
- Species diffusion
- Heat generation and conduction





Anode (Ni/YSZ) and cathode (LSM/YSZ) porous electrodes
- On-anode steam reforming and water-gas shift reaction
- Heat conduction
- Current conduction
- Species diffusion

Anode and cathode reaction zones
- Electrochemical reactions
- Heat generation

Interconnect (ferritic steel)
- Heat conduction
- Current conduction

Flow passages
- Heat convection
- Plug flow of gas

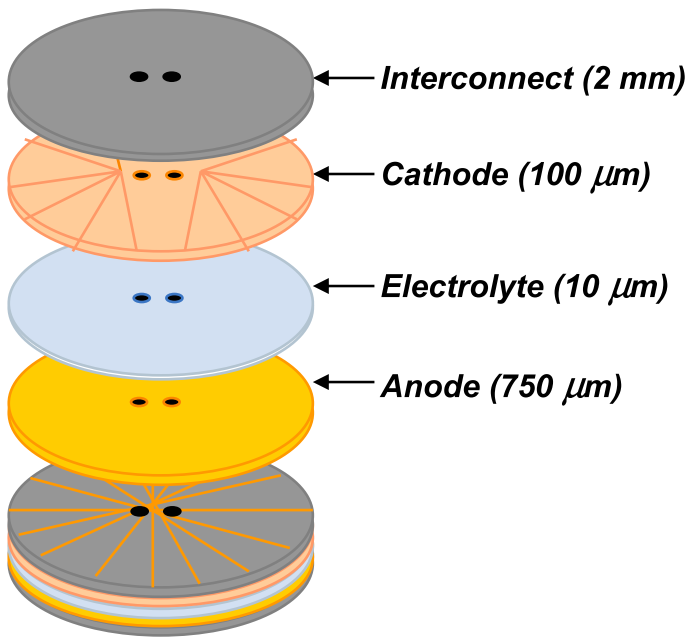
Electrolyte (YSZ)
- Ion conduction
- Heat conduction

- **LSM**: Lanthanum Strontium Manganate
- **YSZ**: Yttrium Stabilized Zirconia

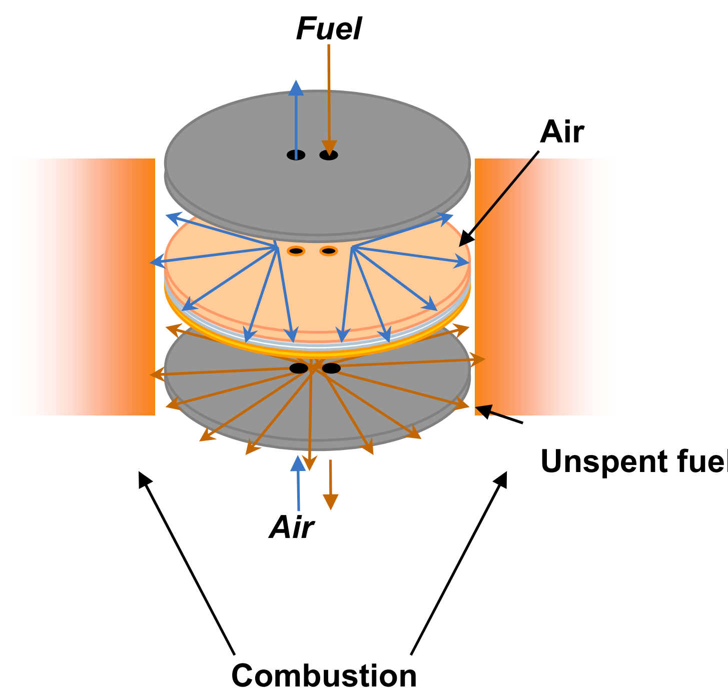
We considered a circular stack architecture for this investigation.

Radial Planar Anode-Supported SOFC Schematics

Cell/Stack Structure



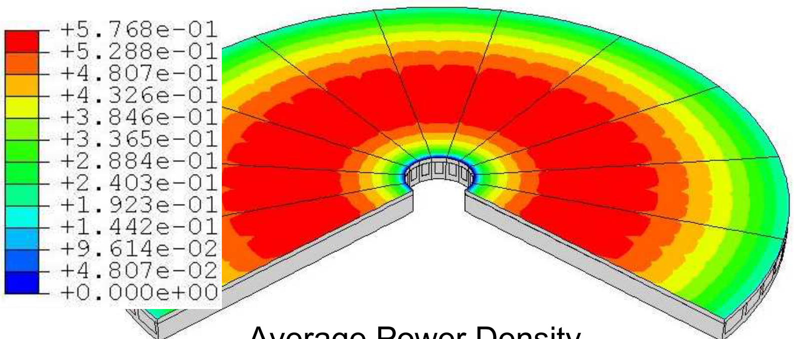
Flow Field



Note: Manifolding design not in detail

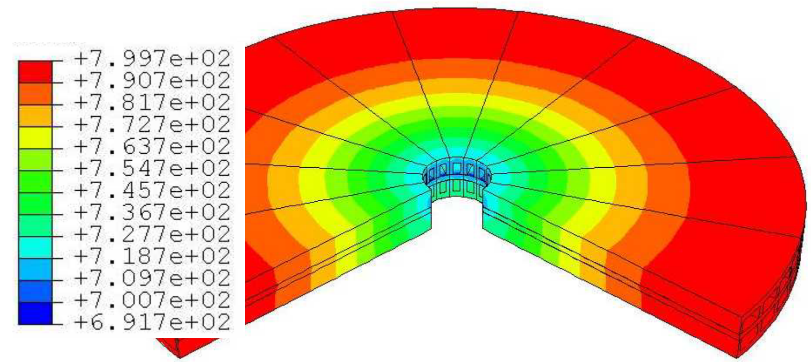
The results demonstrated that reduced cell operating temperature might allow internal reforming without causing damaging stresses.

Power Density Distribution, mW/cm^2

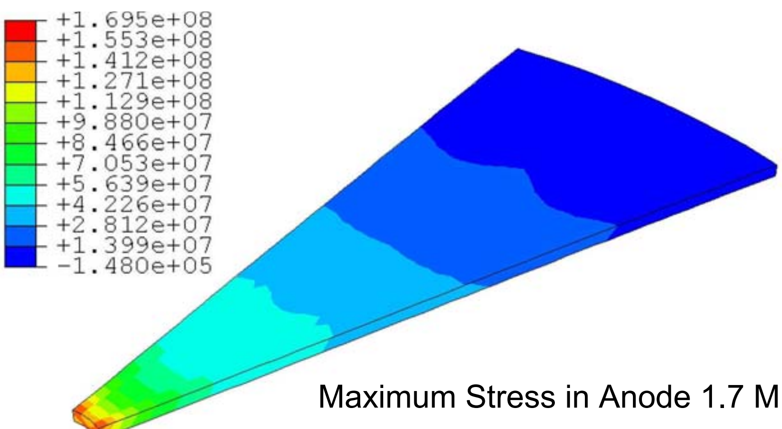


Average Power Density
0.43 W/cm^2

Temperature Distribution, °C



Stress Distribution, Pa



Maximum Stress in Anode 1.7 MPa

Operating Conditions	
Pressure	1 bar
Fuel utilization	90%
Internal reforming	100%
Inlet gas temperatures	650°C
Exit gas temperatures	800°C
Cell radius	5 cm
Contact resistance	No

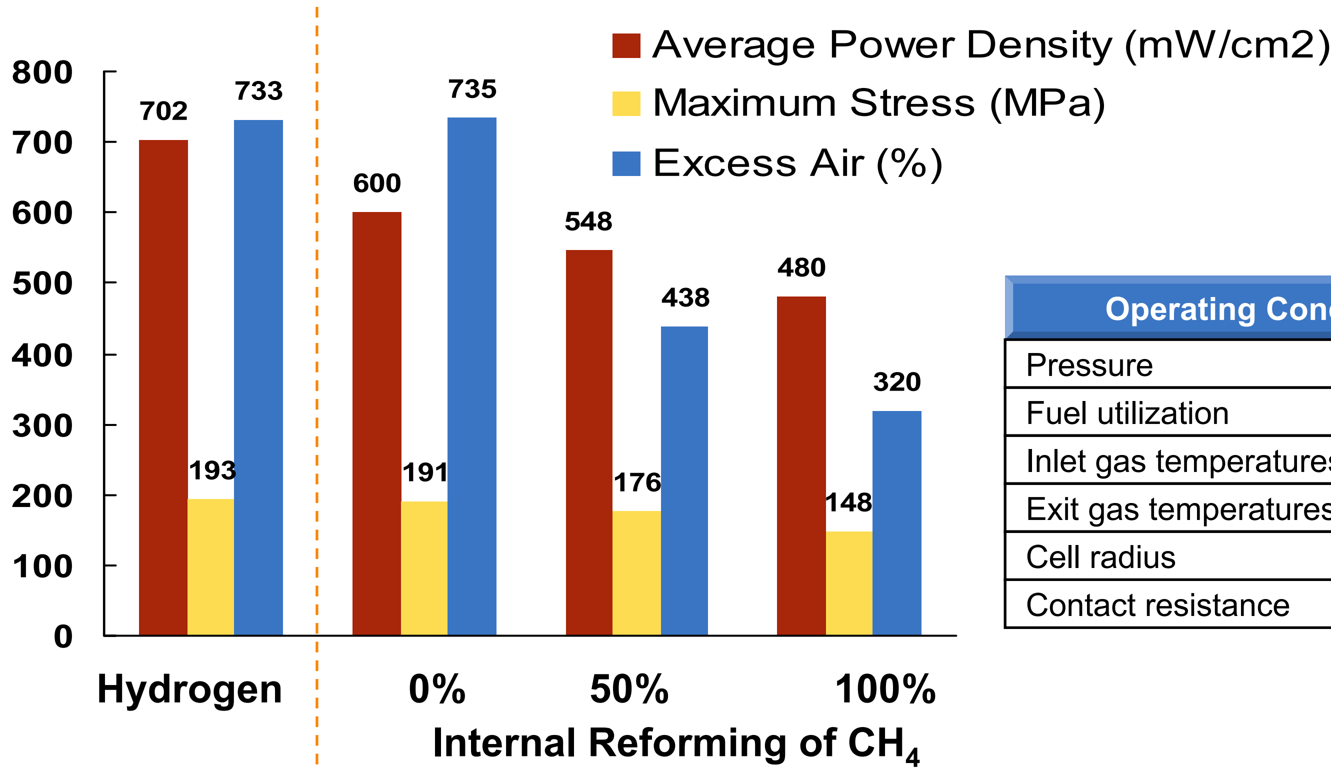
A sensitivity analysis was performed over a range of parameters and the results were used for the design of the SOFC stack module.

Conditions used for sensitivity analysis	
Parameter	**Value**
Pressure (bar)	**1, 3***
Fuel utilization (%)	**50, 90***
Internal reforming (%)	**50, 100***
Inlet gas temperatures (°C)	**650*, 700**
Exit gas temperatures (°C)	**800* , 900**
Cell radius (cm)	**5, 18***
Anode thickness active for methane reforming (μm)	**65*, 300**
Contact resistance (Ω cm²)	**0 , 0.1**

* base case values

Model results show that 100% internal reforming leads to lower stress levels than than either partial pre-reforming or pure H_2.

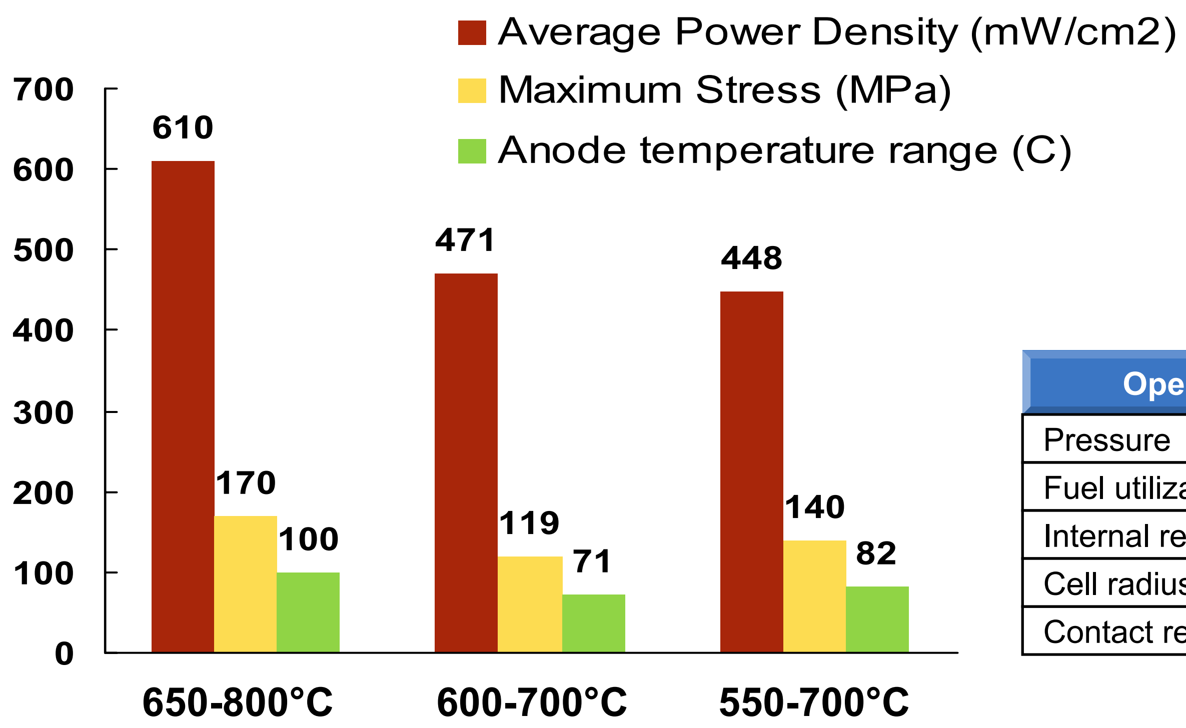
Effect of Internal Reforming



Operating Conditions	
Pressure	1 bar
Fuel utilization	90%
Inlet gas temperatures	650°C
Exit gas temperatures	800°C
Cell radius	5 cm
Contact resistance	No

Power density decreases by approximately 25% when the fuel cell temperature range is reduced from 650-800°C to 550-700°C.

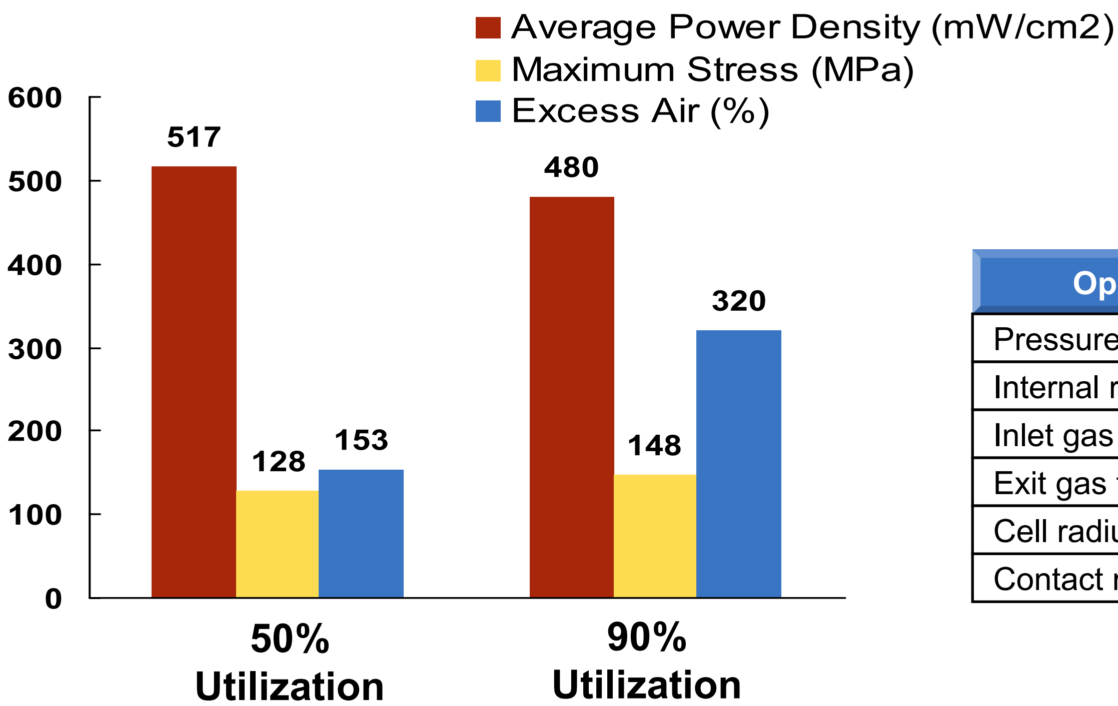
Effect of Operating Temperature



Operating Conditions	
Pressure	3 bar
Fuel utilization	90%
Internal reforming	100%
Cell radius	5 cm
Contact resistance	No

Under high fuel utilization the average power density decreases and stress in anode increases compared with low utilization scenarios.

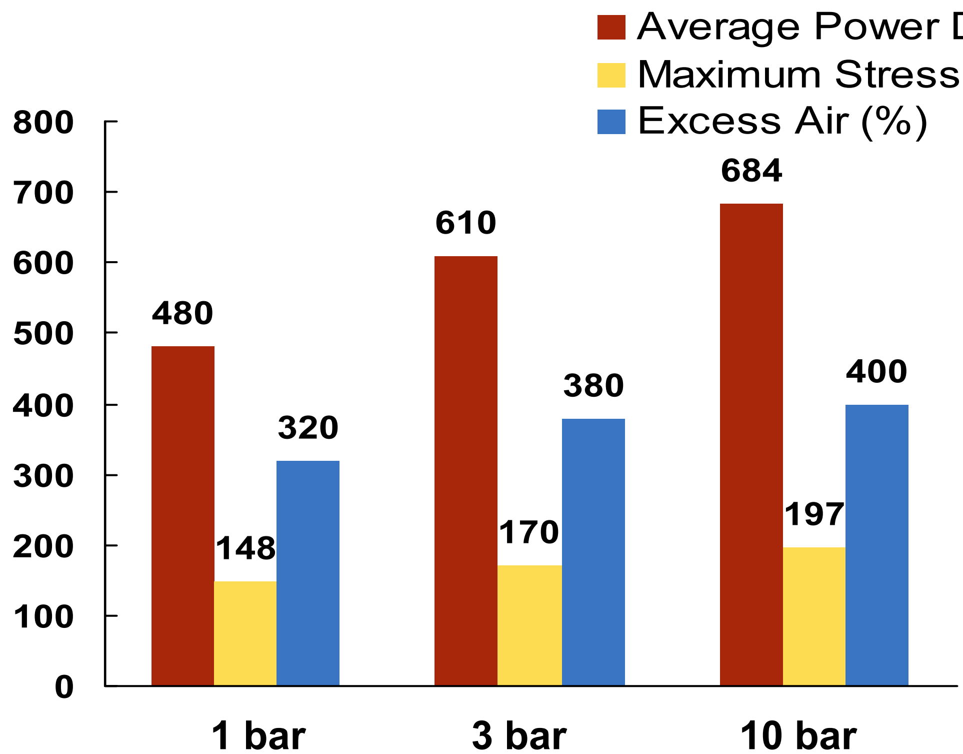
Effect of Fuel Utilization



Operating Conditions	
Pressure	1 bar
Internal reforming	100%
Inlet gas temperatures	650°C
Exit gas temperatures	800°C
Cell radius	5 cm
Contact resistance	No

Increasing operating pressure from 1 to 3 bar leads to 30% improvement in power density, but increasing from 3 to 10 bar leads to only 12% improvement in power density.

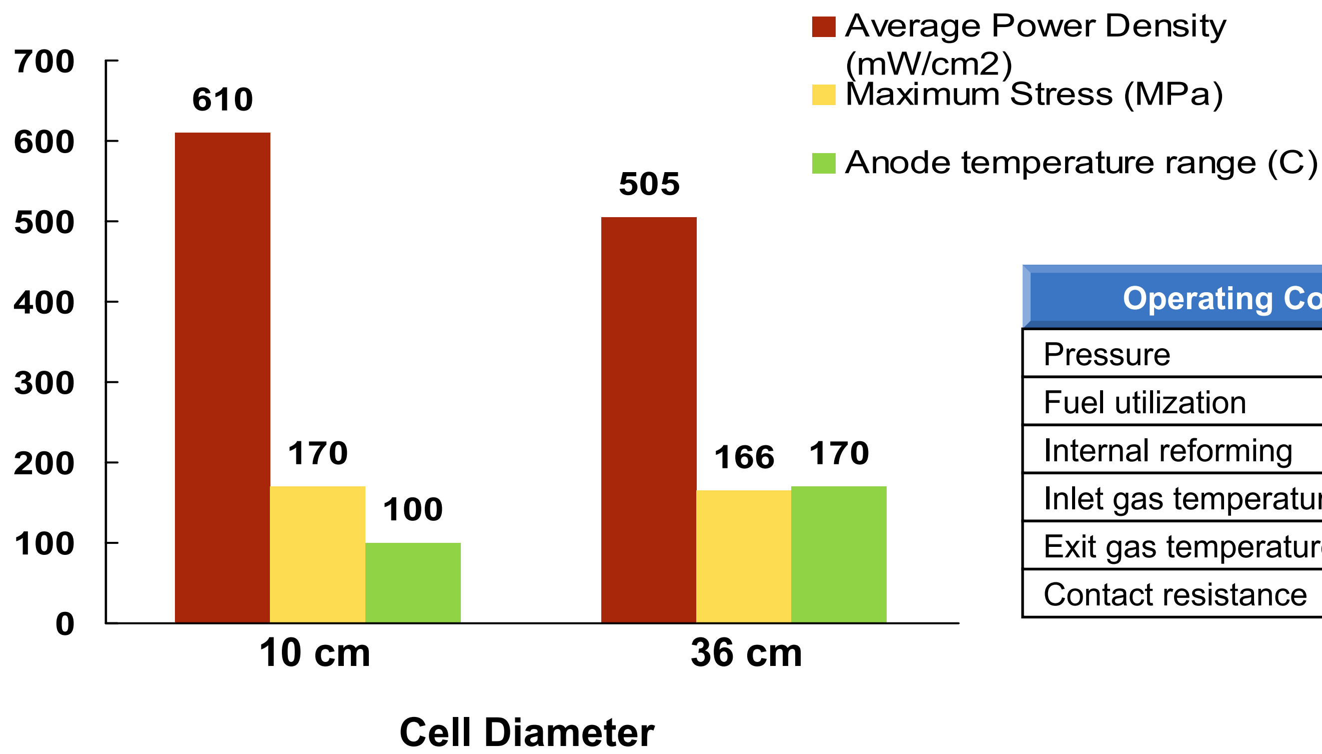
Effect of the Operating Pressure



Operating Conditions	
Fuel utilization	90%
Internal reforming	100%
Inlet gas temperatures	650°C
Exit gas temperatures	800°C
Cell radius	5 cm
Contact resistance	No

The stress levels in the cell are not strongly influenced by cell diameter indicating that cells larger than 5 cm are feasible, however the power density is reduced.

Effect of the Cell Size



Operating Conditions	
Pressure	3 bar
Fuel utilization	90%
Internal reforming	100%
Inlet gas temperatures	650°C
Exit gas temperatures	800°C
Contact resistance	No

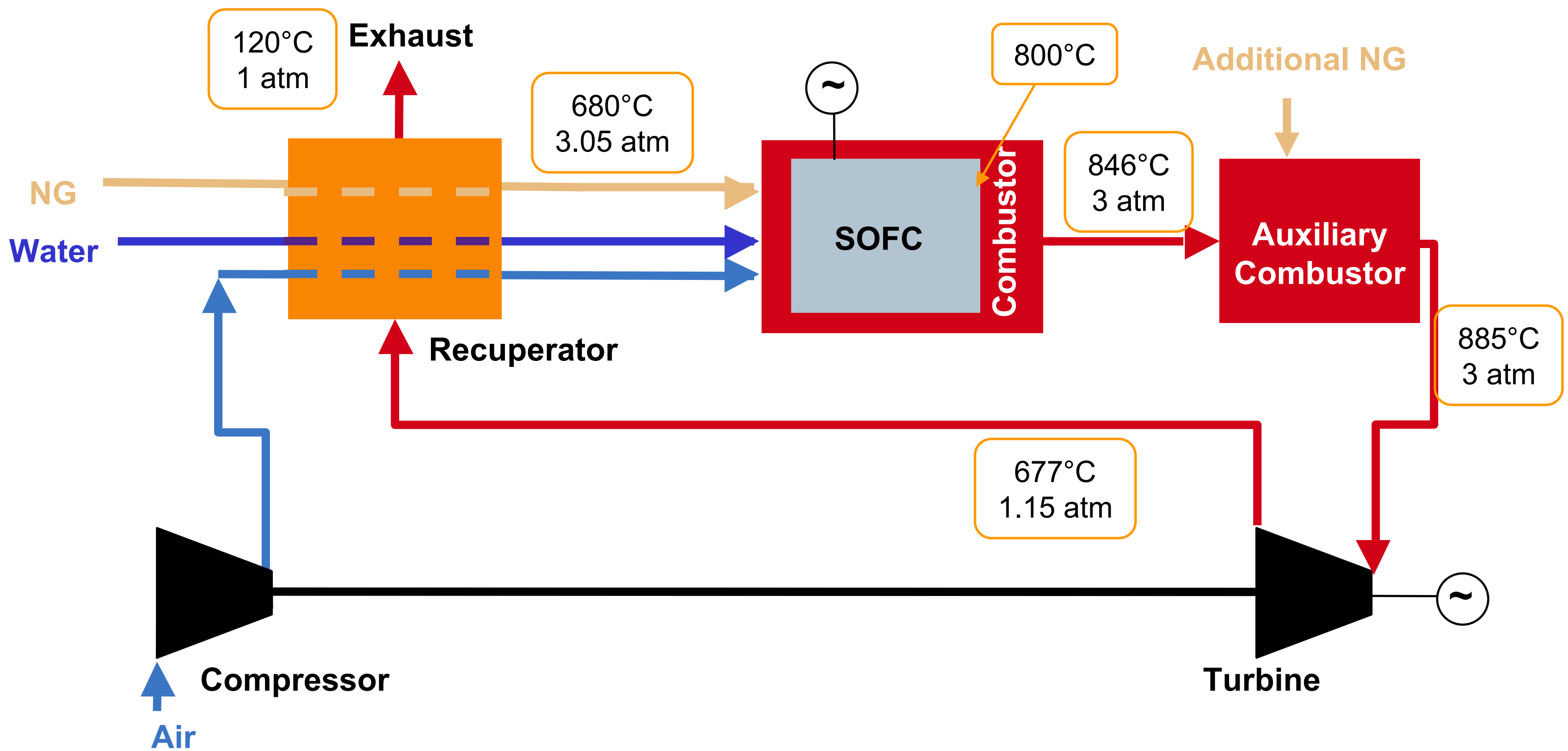
The base case SOFC stack operating parameters were assumed for conceptual system modeling.

SOFC Stack Operating Parameters for System Modeling/Design	
Parameter	**Value**
Fuel Cell Radius	18 cm
Operating Pressure	3 bar
Inlet Temperatures (Fuel and Air)	650°C
Maximum Stack Temperature	800°C
Extent of Internal Reforming	100%
Fuel Utilization	90%
Contact Resistance	No

Base Case Results	
Parameter	**Value**
Average power density	505 mW/cm^2
Peak power density	645 mW/cm^2
Excess air requirement	392
Temperature change across the stack	170°C
Maximum stress in anode	166 MPa

Direct SOFC/GT hybrid system based on base case SOFC operating conditions was modeled.

System Configuration



Hybrid system performance is based on a base case SOFC operating point and is not optimized.

System Operating Conditions	
Parameter	**Value**
Compressor Adiabatic Efficiency	75%
Turbine Adiabatic Efficiency	85%
SOFC Fuel Utilization	90%
SOFC Operating Voltage	0.7 V
Excess Air	390%
Steam/Carbon	2.3

Modeled Hybrid System Performance	
Parameter	**Value**
SOFC Efficiency	51%
Overall System Efficiency	64%
Turbine Output Fraction	20%
Auxiliary Combustor Fuel Fraction*	7%

* The model shows auxiliary fuel is required to ensure appropriate inlet temperature regime for the SOFC stack.

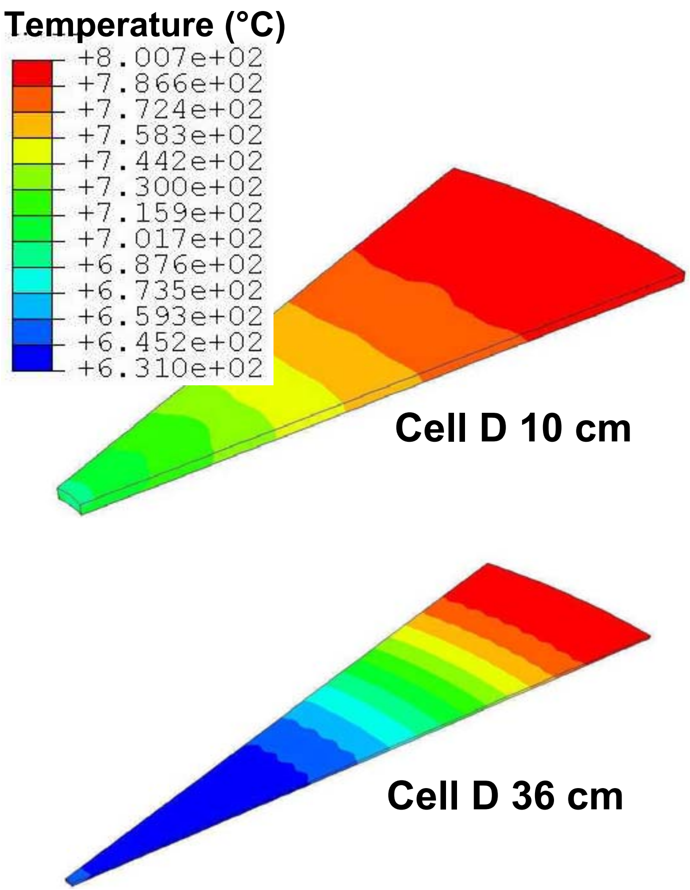
The integrated SOFC model can be used to quantify the implications of the scale-up of anode-supported SOFC cells and stacks.

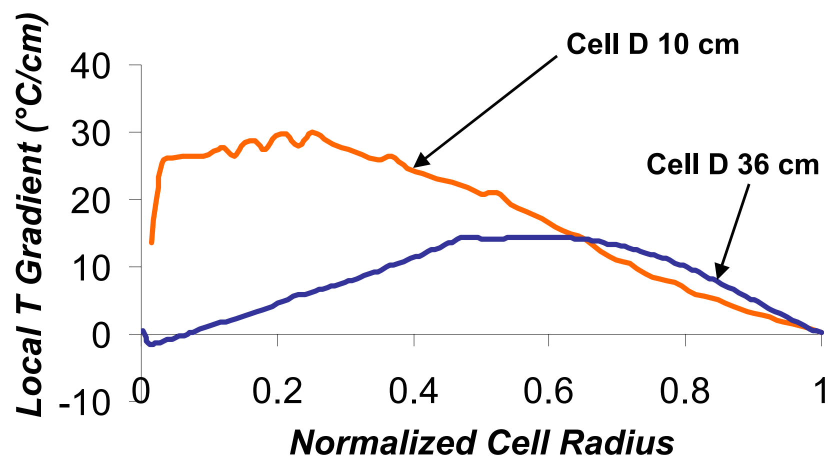
- Anode-supported SOFC stacks operating at modest temperatures (650-850°C) provide an attractive option for use in MW-class SOFC systems.
- The sensitivity analysis revealed a number of advantages for the planar anode-supported SOFC technology:
  – Reduced cell operating temperature might allow internal reforming without causing damaging stresses
  – The stress levels in the cell are not strongly influenced by cell diameter indicating that cells larger than 5 cm are feasible
- In particular, the model allows to investigate the critical operational and performance issues to design stacks for the MW-scale systems.

Appendix

Local temperature gradient is higher in a small cell, which is likely to be the reason for lower maximum stress in the anode in a larger cell.

Effect of the Cell Size





Operating Conditions	
Pressure	3 bar
Fuel utilization	90%
Internal reforming	100%
Inlet gas temperatures	650°C
Exit gas temperatures	800°C
Contact resistance	No